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TRACKING EFFICIENCY AS A FUNCTION OF INTERMITTENT PHOTIC STIMULATION

by

© GREGORY A. MacDONALD

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UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Tracking Efficiency as a Function of Intermittent Photic Stimulation" submitted by Gregory Alan MacDonald in partial fulfilment of the requirements for the degree of Master of Science.

Abstract

This research represents the first extension of the alternation of response theory to motor processes. Two experiments were designed to test the ability of this theory to predict tracking efficiency under intermittent photic stimulation. Previous investigations of motor control under flicker varied rate of photic intermittency but failed to study a range of relevant PCFs. The interaction of rate with PCF is of prime importance to the alternation theory since it is the physical specification of the temporal interaction between patterns of neural discharge and recovery of channels in the visual system.

In the first experiment, two groups of 12 Ss each were matched for motor skill and percentage use of visual information in a pursuit rotor task. Ss were tested on 13 treatment conditions which included rates of 4.9, 9.8, 23 Hz, and fusion crossed with 0.125, 0.25, and 0.50 PCF, and a control condition of steady illumination. Tracking efficiency was optimally reduced ($P < 0.01$) under 5 Hz and 0.25 PCF, the conditions which have previously been shown to disrupt visual acuity and brightness processes.

A second experiment tested the differential effects of wavelength on tracking efficiency under 5 Hz and 0.25 PCF. Two matched groups of 5 Ss were tested on narrow wavebands approximating red, orange, yellow, green, and blue. Tracking

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errors occurred more frequently under blue than green and orange, and more frequently under green and orange than under red and yellow. The results were significant ($P < 0.01$). These color data closely resemble data collected on desaturation under flicker by Ball and Bartley (1965).

The results were discussed at an empirical level in terms of their relationship to brightness and acuity. Further discussion at a theoretical level related the data to temporal factors involved in visual acuity and color coding.

Acknowledgements

I should like to thank my advisor, Dr. T.M. Nelson, for his invaluable guidance throughout the entire development of this thesis. I should also like to thank Drs. F. Bleck and C. Bourassa for their cooperative suggestions and criticisms of the research.

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To Herman Tennessen whom I admire and respect. Unlike the rest of us, he realized ages ago how ludicrous western values are, and dropped right out.

Introduction

Attempts to describe and explain man's visual experience of the world can be separated into two classes of symbolic communicative devices, the spatially based theories and the temporally based theories. An outline of the development of these classes of theories is presented in this thesis in an attempt to clarify the limitations and capacities of a temporally based theory to account for visual phenomena which have not been adequately explained by spatial theories.

An hypothesis relating motor performance to intermittent photic stimulation is derived and tested within the alternation of response theory. The results of two experiments demonstrate the extension of the predictive domain of this theory from a sensory data base to a restricted class of motor events. Interpretation of the results at an empirical level relates them to the expectations of the alternation of response theory. Discussion at a theoretical level attempts to integrate color coding data with temporal accounts of visual acuity.

Theoretical Background: The Origins and Limitations of Spatial and Temporal Accounts of Visual Perception

Accounts of visual perception in terms of spatially contingent events have had a long developmental history which is quite different from that of the temporal accounts. Early explanations of various interesting visual phenomena by Greek and Egyptian intellectuals maintained a close liaison with the ordinary psychological experience of spatial contiguity. Ptolemy's (127-141 A.D.) geocentric theory of the universe and his report of the "vault of heaven" reflect his concern with immediate experience rather than abstractive explanations within physical theory as the true data base of science. Later explanations of spatial phenomena indicated an increasing dependence upon theoretical models which by their scientific nature had become separated from ordinary experience. Many of the modern scientific theories of spatial perception are almost totally interpretable within highly restrictive mathematical languages like Euclidian geometry. The elaboration of this theoretico-linguistic device from man's more primitive notions of space has been structured primarily by non-academic influences such as personal considerations and the demands which political and economic factors have placed upon it. Geometry, for example, began in ancient Egypt in the mensuration of land and defining of

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property boundaries after repeated floodings of the Nile. Here in its most rudimentary form, techniques consisted of crude methods of calculation and isolated facts of observation which derived ultimately from man's ordinary understanding of spatial relationships. Only later when it was introduced into Greece by Thales of Miletus (640-546 B.C.) were various more "intellectually respectable" attempts made to reduce geometry to a metrical science. Euclid (c. 300 B.C.) is, of course, credited with the most rigorous presentation of geometry in a series of logically related propositions based on a few axioms and definitions. The later application of the science to non-agrarian[1] studies has been influenced to a great extent by the charisma of Euclid who, like Aristotle, gained the reputation of being infallible. This has since proved to be a distinct bar to scientific progress.

Temporal theories have not undergone the same sequence of gradual dissociation from ordinary experience as the result of increasing alliances with other theoretical and technical systems. They have arisen directly as a result of technological and methodological advances made in the study of the nervous system within the last hundred years. Thus temporal theories have always been closely related to representational systems which have long been divorced from man's subjective experience of the world.

The fact that both spatial and temporal theories were originally meant to deal with restricted classes of events in applied fields, and that they have been borrowed by psychology

at a relatively late stage in their development, has had two important limiting consequences for visual theories.

First, while the subjective or first-person nature of psychological data has presented no major technical problems with regard to its incorporation into the theoretical framework of a third-person or objective scientific language, the extent to which these data can be adequately handled by commutative logic is, at best, tenuous and is certainly not well understood. An interesting illustration of this type of limitation comes from a linguistic interpretation of Zeno's paradoxes of time and motion. When considering the hypothetical race between Achilles and the tortoise, there is no question in our experience that Achilles overtakes the tortoise and wins the race. However, when we set out to describe the events of this race within some formal conceptual system, we find contradictions arising. This leaves us with the notion that the paradoxes of motion arise not from inconsistencies between elements of thought _per se_, but rather between the thought and the particular way in which it is restricted by the language form used to convey it.

Secondly, while man's most basic experiences of both time and space have a common origin in his ordinary perception of contiguity, the development of two separate classes of theoretical languages to describe these experiences has resulted in an artificial dichotomy between time and space which psychology has not yet resolved.[2]

Insights into both these limitations come from an understanding of the processes of restriction and precision involved in the translation of ordinary psychological concepts into theoretical language systems.

The data of psychology (cognition, motivation, perception, etc.) are highly personal and not easily described by reference to physical objects or events. In the interests of science, formal languages attempt to make precise the concepts with which they deal. In doing so they not only restrict the definitions of the concepts or elements, but also their use, i.e., the ways in which elements in the system may be related to each other. Such are the properties of commutative logic: reflexivity, transitivity, and symmetry. The data of ordinary experience have a broad spectrum of connotative interrelationships. The problem lies in the failure of an "objective" conceptual system to represent all facets of structure which exist at the empirical level in a one-to-one correspondence within the written language. The ordinary language of visual experience admits to more variability of conceptualization than does the scientific language used to describe it.

In summary, it is suggested that many of the problems involved in the understanding of human experience arise from attempts to map psychological data into theoretico-linguistic systems which have been developed to deal with entirely different problems.

Theoretical Contributions of Structuralism and Neurophysiology

Until the present century, the mainstream of epistemological thought considered man's visual experience of the world to be spatially coded within his perceptual system. The earliest scientific theories of perception differentiated from this tradition, and developed within the conceptual framework of German structuralism in the nineteenth century. The Young-Helmholtz trichromatic theory of color vision (in Helmholtz, 1860) and Fechner's (1860) psychophysical work on brightness JNDs are typical examples of spatially based theories. Many of these early spatial accounts of vision dealt primarily with immediately discernible phenomena such as the localization of surfaces in space. Explanations of size, shape, distance, and depth perception for example, commonly involved an integration of the notions of past experience with an understanding of the geometrical properties of objects in the environment and corresponding spatial interrelationships of patterns of stimulation falling on the retina. The epitome of this approach is presented in the first volume of Helmholtz's Handbuch der Physiologischen Optik (1856) where the eye is treated as a fine optical system, similar to, but more flexible than, a camera. Helmholtz's basic sensory pattern or Perzeption when modified by unconscious inference became an Anschauung. Anschauungen better accounted for phenomena such as size and shape constancy which were not well handled in terms of purely physical operations of the eye.

A more basic class of visual phenomena involves the immediate

discrimination of properties such as brightness, hue, saturation, and edge. These phenomena were not considered to be products of psychological factors like past experience and were better explained within physics and physiology, the disciplines which had most clearly specified the stimuli producing them. Although early spatial theories made considerable progress in the understanding of color and brightness phenomena, their success was limited largely as a result of their concern with operations taking place in the periphery of the visual system. Partially for reasons of limited technology, these theories restricted their scope to investigations of relationships either between these phenomena and retinal activity, or between the sensory phenomena and the physical conditions of stimulation entirely neglecting the retina. They had no knowledge of the transformations in photochemical energy which take place between the retina and the higher centers of the nervous system.

Recent technological and methodological advances in the study of the nervous system have opened new channels of investigation into spatial aspects of these visual phenomena. Spatial accounts of vision now reflect concern with anatomical interrelationships in the retina, especially with lateral interactions and the spatial representation of afferent information in receptive fields, etc. Spatial approaches are more concerned with which fibers are conducting the information than with when information is being conducted.

These advances in neurology have also opened new channels of investigation into temporal aspects of vision. The special virtue of the temporal mode of analysis is that neural activity lends itself well to quantification in terms of latencies, rates of discharge, and recovery times. The results of these time variations are precise and tend to reflect the operation of the nervous system in a nativistic way. However, temporal approaches to these phenomena are not without limitations. A major criticism is that the mathematical parameters of time, e.g. duration and frequency, have structured temporal analyses to deal with successive events only at the expense of simultaneous events. Many spatially contiguous events presented simultaneously are summated by the visual system and cannot be resolved as separate events. Temporal approaches include only nominal provisions for dealing with such events and these provisions are more _post hoc_ than integral parts of the developmental history of the system. This type of restriction ultimately limits such approaches to accounts of sensory data and other types of non-spatial visual data.

A second criticism takes the form of suggesting that the temporally based theories are unduly parsimonious in that they attempt to describe purportedly complex patterns of neural activity in terms of a few simple parameters of a single variable. Temporal accounts of perception are better defended on this point. They are first and foremost psychological theories which are

concerned primarily with experience and only secondarily with neurophysiological correlates of experience. They were not meant to be crude precursory mathematical analogies to underlying physiological or biochemical processes. These neurological explanations of vision are at the present time concerned only with the physical operation of the nervous system. With respect to the empirical foundations of vision, they have remained conceptually discrete.

Consequently, even though the parametric limitations of the temporal approaches are acknowledged, such approaches are not considered theoretically epiphenomenal to more sophisticated explanations within neurophysiology or biochemistry. They do, however, serve as a basis for future theorizing on the physiological processes involved in visual experience. For the present state of our knowledge, the prime function of visual theories based on temporally contingent events has been to provide us with insights into an entire class of visual phenomena not previously understood.

Empirical Background

The earlier German work involving experimental manipulation of temporal variables concentrated on single-pulse and two-pulse phenomena. This work implicated duration of stimulation and duration between pulses as analogues of discharge and recovery times of fibers in the visual system.

Other visual phenomena arising from the ordinary experience of flicker, for example phenomena induced by the spinning of toy tops, popularized the method of intermittent photic stimulation in the nineteenth century as a temporal device for studying the visual system. The study of trains of photic stimulation is concerned not only with pulse durations and separations between pulses, but also with periodic phenomena induced by cyclic characteristics of the train.

Several important classes of visual phenomena are associated with flicker:

(1) Prevost, Fechner, and Benham (reported by Cohen and Gordon, 1949) demonstrated that various hues and saturations will arise from full spectrum stimulation under certain conditions of stimulus intermittency.

(2) Critical flicker frequency (CFF) is the rate of flicker above which intermittently presented targets appear to be continuously illuminated. (Bartley and Nelson, 1960a, 1960b; Nelson, Bartley, and Bleck, 1964; Ranney and Bartley, 1964.)

(3) Talbot's law states that the brightness of an intermittent stimulus which appears to be fused (i.e., above CFF) is the same as that of a steady stimulus having the same fraction of intensity as the pulse-to-cycle fraction (PCF)[3] of the intermittent stimulus. (Plateau, 1830; Talbot, 1834.)

(4) Brightness enhancement refers to the perceptual fact that under certain rates and PCFs an intermittently illuminated target will appear brighter than a steadily illuminated target of the same intensity (Bartley, 1938; Bourassa and Bartley, 1963; Nelson, Bartley and Ford, 1963).

(5) Color bleaching or desaturation refers to the phenomenal shift in hue and saturation of part spectrum targets when they are presented intermittently. (Nelson and Bartley, 1961.)

Color bleaching has been studied only recently, but investigations into the other classes of visual phenomena related to flicker were relatively independent of each other before the mid-thirties. Bartley and his colleagues have been the first to investigate systematically an extended range of phenomena related to flicker. They have organized and interpreted the various findings within a temporal framework called the alternation of response theory.

The alternation of response theory proposes that the visual system consists of a number of parallel channels or longitudinal

circuits which connect the peripheral receptor elements to the brain. In the optic nerve, a single fiber is a functional unit and therefore constitutes a channel. At the retina, complex anatomical interrelationships involving bipolar cells, amarcrine and horizontal cells, etc., complicate the histological delineation of a channel, but conceptually, it remains a functional unit connecting the eye and the brain. The significance of the theory for the present research can be summarized by three concepts; periodicity, alternation, and reorganization.

The concept of periodicity derived from the early work of Bartley and Bishop (1933) on electrical stimulation of the optic nerve of the rabbit. They discovered that the visual system was periodically receptive to photic stimulation. The duration of the cycle was about 100 ms, the same as that of the alpha-rhythm. Various theoretical connections between these two concepts have been developed since 1933. As periodicity relates to the total pathway, or to cells in the cortex, it is considered a cortical excitability cycle. As it relates to activity in a single channel, it can be considered an activity-recovery cycle.

Under steady illumination, the channels in the visual system are in a state of alternation; some are firing while others are recovering. Time differences in latencies of discharge, conduction rates, and recovery rates in different channels provide the mechanism for alternate firing and recovery of neural pathways in the system. These time differences can be explained at an anatomical level in terms of structural differences in the

fibers such as length and thickness, myelination, and number and properties of synapses, etc., or at a more refined level in terms of sequences of biochemical reactions in the pathway. The existence of these time differences in patterns of mass discharge forms the basis of the concept of alternation.

The wave form of the cortically evoked potential produced at the onset of a train of photic stimuli typically shows an early peak of maximal amplitude which is followed by several smaller irregular peaks. Eventually, the wave form exhibits a sequence of regular peaks whose periods are consistent and whose amplitudes are greater than those of the irregular peaks, but not so great as that of the initial peak. The temporal explanation for this wave form is that prior to stimulation, the visual system is in a state of relative quiescence. Since most channels are at rest at the time of stimulation, they are capable of relatively synchronous response. The simultaneous firing of a large number of fibers accounts for a summated response to the stimulus which is represented by the first wave of the evoked potential. As various channels discharge and recover at different rates, patterns of neural activity are distributed over time and a certain duration elapses before synchrony of discharge becomes optimal. This period of irregular activity which precedes synchronous discharge is referred to by Bartley as the period of reorganization.

According to the alternation of response theory, certain

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conditions of stimulus intermittency program the channels to fire synchronously and thus produce bunching in the optic tract. This disjunctivity of input is purported to be the cause of the various phenomena associated with flicker.

The physical conditions for optimal synchrony of discharge or maximum bunching in the visual system can be specified by the interaction between rate of stimulus intermittency and PCF. Five or ten Hz and 0.25 PCF are, in general, considered optimal conditions for this bunching, and have been demonstrated to produce maximal brightness enhancement, color bleaching, and hue shifts.

Empirical data supporting the contention of an optimal PCF of 0.25 are quite consistent. PCFs bracketing 0.25, for example 0.125 and 0.50 do not produce as great differences in brightness (Bartley, 1938), hue shifts (Ball and Bartley, 1965), or as much desaturation (Ball and Bartley, 1965; Nelson and Bartley, 1961).

Data supporting an optimal rate are not consistent. Bartley predicts maximum disruption in visual processes near 10 Hz, the theoretical excitability cycle upon which the alternation theory is based. Bartley (1968) and Schneider and Bartley (1966) support this contention. However, recent evidence has contested it. Rabelo and Grüsser (1961) and Nelson, Bartley, and Ford (1963) have suggested that the rate producing optimal synchrony is 5 Hz.

Considerable knowledge related to hue shifts and desaturation

of part spectrum targets has accumulated during the past decade. Ball and Bartley (1965) have shown that both these phenomena are dependent upon wavelength as well as rate and PCF. Under intermittency conditions of 9.8 Hz and 0.25 PCF they found a bi-modal desaturation curve with maxima near 490 mμ and 630 mμ, the former being the point of highest desaturation. The minimum point of desaturation lay between these two points at about 575 mμ. The magnitude of hue shifts according to Ball and Bartley is generally dependent upon rate and PCF, but their direction is dependent upon wavelength. No hue shifts under conditions of 9.8 Hz and 0.25 PCF occur near 500 mμ and 575 mμ, the points of maximum and minimum desaturation. The direction of shift above 575 mμ and below 500 mμ is towards the shorter wavelengths. The direction of shift between these two points is toward the longer wavelengths. Nilsson's (1969) hue shift data agreed with those of Ball and Bartley for wavelengths up to 610 mμ, but above this point Nilsson reported shifts towards the longer wavelengths.

Another body of research has been concerned with visual acuity and edge formation under intermittent photic stimulation. Gerathewohl and Taylor (1953), Nachmais (1958), and Ratliff (1961) had suggested that conditions for brightness enhancement should improve visual resolution in the same manner as does the visual flux. This suggestion was grounded in the fact that both temporal changes and quantitative changes in the visual flux result in changes in luminosity. It reflects the erroneous

assumption that stimulus factors which increase brightness necessarily increase visual acuity. Although this is a fact for illumination intensity (Hecht, 1928; König, 1897), it has been rejected for brightness enhancement. Gerathewohl et al. failed to find enhanced acuity under flicker. No explanations from these studies were forthcoming. Bartley and Ball (1968, 1969), Bartley, Nelson, and Soules (1963), and Bourassa and Bartley (1965) have shown that visual acuity is reduced under intermittency conditions which produce brightness enhancement. These findings suggest that temporal disruption of normal visual processes is responsible for reduction in acuity as well as for various brightness and color phenomena.

Background to the Specific Problem

During World War Two an abnormal number of plane crashes occurred which involved single engined aircraft landing into the setting sun. Johnson (1963) reported similar incidents involving helicopters. Many of these crashes were attributed to "flicker vertigo", a dizziness induced by the flickered appearance of the sunlight through the propellor blades. With the advent of the jet plane, the practical necessity for studying this phenomenon diminished. The focus of interest shifted to related problems involving motor efficiency as a function of certain perceptual conditions. Two lines of study emerged, the first being concerned with flashblindedness. Specifically, it was concerned with visual resolution and the pilot's ability

to make adaptive motor reactions immediately following the single flash of a very bright light. The second line of research, from which the present study derives, involves motor control under conditions of stimulus intermittency.

Battig, Gregg, Nagel, Small, and Brogden (1954) found a curvilinear (U-shaped) relationship between rate of photic intermittency from 5 to 15 Hz and tracking efficiency. Battig, Voss, and Brogden (1955) replicated this study under conditions of controlled illumination intensity and PCF of 0.50. Their results showed no optimal rate of intermittency for tracking efficiency, but rather a direct linear relationship between the two variables. Bach, Sperry, and Ray (1957) reported a marked impairment of performance in a rotary pursuit task under intermittency of 9 Hz. However, the design of their study did not provide for the adequate control of illumination intensity. The ambient steady illumination (control) was 20 ft-c whereas the average cycle illumination of the flickering light was 0.1 ft-c. Since illumination intensity has a known effect on acuity and therefore on motor performance which involves visual information, the results could be attributed to this drop in intensity. Slak and Brožek (1965) unsuccessfully attempted to generalize the results of Bach <u>et al</u>. (1957) by varying rate of intermittency. Their failure to do so may be due either to their use of PCF 0.50 or to the nature of the perceptual motor tasks used which involved no adjustments to moving targets.

The existence of a cerebral rhythmic scanning mechanism which "samples" the target at about 10 Hz has been proposed by Ellingson (1956) and White (1963). Harter, Eason and White (1964) suggested that tracking efficiency under photic intermittency could be predicted by a "psychological moment" model based upon such a rhythm. With a background illumination of 5 ft-c they found a U-shaped relationship between rate of flicker and tracking performance on a pursuit rotor. Performance was optimally reduced under 9 Hz. With no background illumination, they found a monotonic relationship between these two variables. Tracking performance decreased sharply as rate was reduced from 12 Hz to 2 Hz. Intermittency was provided by a Grass Model PS2 photo-stimulator which maintained a constant flash duration at 10 μsec.

The results of these studies are equivocal. The author suggests that this may be due to the inadequate control of variables now considered important for the temporal organization of activity within the visual system, specifically, illumination intensity and PCF.

Hypothesis

Since visual acuity is necessarily a factor in perceptual-motor tracking, its reduction should be accompanied by a reduction in tracking efficiency to the extent that such a task involves the use of visual information. More explicitly, the alternation of response theory has predictive implications for

tracking efficiency when the target to be tracked is presented intermittently.

The purpose of the present research is to investigate tracking efficiency as a function of rate, PCF, and wavelength of photic input. The specific prediction is that under full spectrum stimulation, maximum reduction in performance on a rotary pursuit task will occur under conditions which have previously shown disruptions in normal acuity and brightness, i.e., 5-10 Hz and 0.25 PCF. The effect of wavelength on tracking efficiency will be investigated in a separate experiment, but no predictions are made concerning a possible relationship between the two.

Method

Two classes of perceptual-motor tasks have been studied under flicker. The first involves types of production-line tasks, for example putting round pegs in round holes. The second involves tracking. Tracking under intermittent photic stimulation was considered preferable for the purposes of the present research since it requires constant motor adjustment to a moving target. This is important in visual research since constant adjustment typically involves the greater use of visual cues than kinesthetic and other non-visual information.

Apparatus

In general, the equipment consisted of a bright light playing on the deck of a pursuit rotor in a relatively dark room (Fig. 1). The light was made intermittent by episcotister discs. The walls, ceiling, etc., were flat black. Dim background illumination was provided by one 100 watt tungsten ceiling lamp.

Tracking device. Since this research concerned itself primarily with motor response as a function of changes in perceptual conditions, the only requirement of the response variable was that it be a gross but relatively consistent measure of motor control. For this reason a simple rotary pursuit tracking task was chosen. A Lafayette No. 203 rotary pursuit apparatus was placed on a black table so that it could be reached easily from a normal sitting

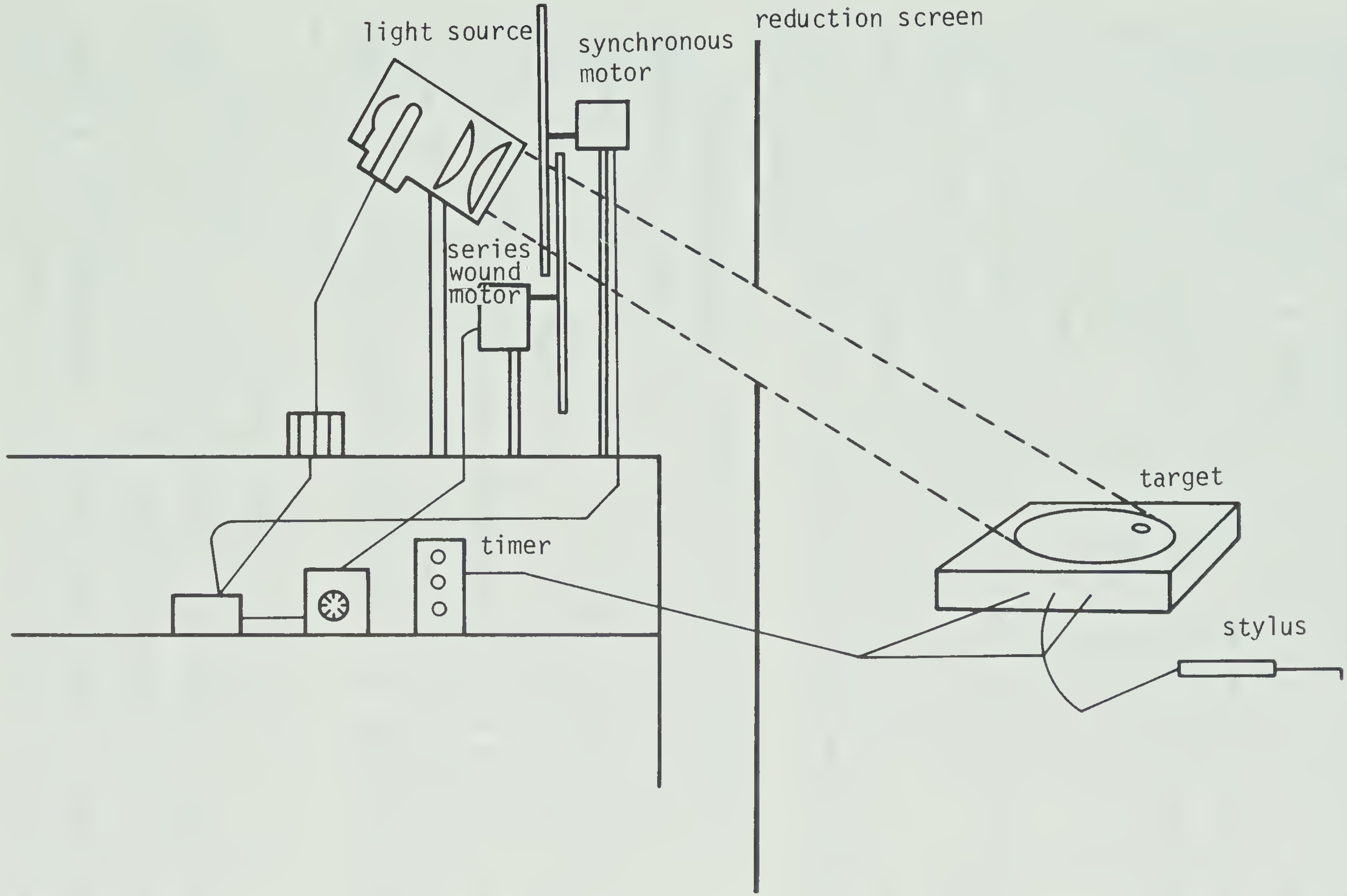

Figure 1: Schematic Diagram
of the Apparatus.

position. The turntable was 31 inches from the floor. It operated on a continual cycle of approximately 40 seconds during which it rotated at a constant rate of 60 r.p.m. (1 Hz) for about 22 seconds and was off for 18 seconds. The target tracked was a 3/4 inch metal disc centered 1 5/8 inches from the circumference of the 10 inch turntable. The tracking instrument consisted of a steel stylus attached by a spring to a wooden handle. The turntable was sprayed flat white to increase reflectance, which measured about 190 ft-L at the center of the turntable. Slight variations in reflectance existed in different parts of the turntable due to the angle of illumination, but these were constant for all subjects.

Recording apparatus. Time on target was recorded in hundredths of seconds as a total of a possible 22.48 seconds, the temporal definition of a trial. The recording apparatus was a Hunter clockcounter (model 120A). A low amperage circuit connected the clockcounter with both the tracking stylus and the 3/4 inch disc on the turntable, in such a way that the clockcounter would record only when the circuit was completed, i.e. when the stylus was touching the disc.

Light source. A tungsten source was chosen for its full spectral range and the linear nature of its spectral composition. The source was a 6 volt, 18 amp. GE-CPG bulb which was run from a CENCO 6 volt transformer. The bulb was placed in a spotlight housing 66 inches from the center of the turntable and projected

through a black reduction screen onto the deck of the pursuit rotor at an angle of about 45^{0}. The light was collimated both by an adjustable parabolic reflector mounted inside the housing directly behind the bulb, and by two opposing convex lenses placed three inches apart in the front of the housing. These optical controls minimized scattering of the light and provided a concentrated beam which was just wide enough to flood the turntable. The undulating train of flicker varied between 190 ft-L, the pulse illumination, and 0.5 ft-L, the ambient steady illumination provided by the 100 watt tungsten bulb.

Flicker apparatus. The light was made intermittent by employing large (15 1/2") black cardboard episcotister discs which were placed between the source and a reduction screen, eight inches from the source. Two motors ran the discs. A synchronous 300 r.p.m. motor, when mounted with the discs, provided flicker at either 4.9 Hz or 9.8 Hz depending on whether the discs had one or two open sectors. A Bodine (NSE 33) 115 volt, 1.5 amp. 5000 r.p.m. series-wound motor controlled by a variac calibrated to 23 Hz and various fusion rates provided the faster rates of intermittency. Three PCF's (0.125, 0.25 and 0.50) were used. Although rates of onset and offset at different positions on the turntable were varied by the wedge-shaped open sectors, they remained constant for every subject.

Color apparatus. The differential effects of wavelength were tested by filtering the light reflected from the turntable.

Sets of two Kodak 3" x 3" Wratten gelatin filters encased in glass were inserted in specially made grey plexiglass goggle frames which were worn by the Ss in Experiment number II. Kodak Wrattens numbered 70, 72B, 73, 74, and 75 whose dominant wavelengths were respectively 678, 605.7, 576, 538, and 490.5 mμ were used to approximate the critical wavebands suggested by Ball and Bartley (1965).

Equal luminosity for each spectral filter was ensured by equating CFF through the appropriate use of Kodak Wratten neutral density filters. Color filters numbered 72B, 73, 74, and 75 required respectively 0.90, 1.10, 1.40, and 1.00 log units ND.

Experiment No. I

This experiment was designed to investigate tracking efficiency on the pursuit rotor as a function of changes in rate of intermittency and PCF.

Subjects

Twenty-four students from introductory psychology classes served as Ss. All were between 17 and 25 years of age and naive with regard to the specific experiment. Nine additional Ss were trained but not tested for reasons given below.

Sources of Variability and Controls

Since the test consisted of a perceptual motor control task which involved large individual differences in response measures under highly similar stimulus conditions, it was necessary to reduce the intra- and inter-subject variability on several dimensions in order to validate the assumption that differences in the dependent variable (time on target) were in fact the result of changes in rate and PCF controlled by the experimenter. Combinations of experimental, statistical, and selective controls were introduced to reduce variability between Ss as well as within Ss.

Inter-subject Variability

Visual factors were roughly equated by selection procedures which excluded students with abnormal color vision and poor or uncorrected visual acuity.

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Three of the 24 subjects were left-handed. Their orientation with respect to the turntable was reversed for the purpose of controlling shadow effects caused by the stylus.

Pre-test training procedures satisfied the requirements of both acquisition of the specific skill involved, and elimination of Ss who demonstrated abnormally poor motor control. Five Ss failed to reach the criterion of 1/2 time on target during two 22 second pursuit rotor trials after 30 minutes of practice. Statistical controls were introduced to reduce normal variability in motor control. A logarithmic transformation was performed on the raw data, and a normal analysis of variance was run on the log differences between 12 experimental (flicker) conditions and a control condition of steady illumination.

A third major source of inter-subject variation arose from the differential use of visual and non-visual cues in the task. With performance under the condition of steady illumination equated, Ss who were highly dependent upon visual information recorded lower scores under flicker than Ss who were more dependent upon non-visual feedback. This variability was measured at the completion of the training session by taking the performance of each S in a three-trial test under conditions of 9.8 Hz and 0.25 PCF as a percentage of his performance under steady illumination. Scores ranged from 17% to 34%. These scores served to separate Ss into two blocks on the basis of differential use of visual and non-visual cues.

One S was not tested for reasons of early fatigue as indicated by verbal reports, steadily reduced time on target after 10 minutes normal practice, and lowering of the elbow of the tracking arm which was charted on a grid fixed to the wall.

Intra-subject Variability

Three Ss were eliminated for reasons of high intra-subject variability. They failed to demonstrate consistent scores on the tracking task for what were considered to be motivational reasons, (the task is boring).

The primary purpose of the pre-test training procedure was to reduce sequential effects such as increase in performance due to learning or practice, decrease in performance due to fatigue or boredom and inconsistent responses resulting from motivational factors. Pre-training to asymptote on the pursuit rotor task reduced unwanted increments in performance. A short (45 minutes) test session interspersed with rest periods reduced decrements in performance. Latin square orders of presentation of the treatment conditions served to distribute the results of any remaining sequential effects over the largest possible domain, thus reducing their influence statistically.

Instructional techniques aimed at reducing inconsistent responses took the form of encouraging the subject to make a reasonable attempt under all conditions. It was stressed that the lack of trying might invalidate results. Ss were also asked to hold the stylus in a consistent manner during all trials

and to remain seated throughout the task. No other special postural controls were exerted on the Ss in order to allow them maximum flexibility in making the adaptive response.

Design

The design involved two repeated 12 x 12 Latin square arrangements (Table 7, Appendix) which were blocked for reasons discussed earlier. Latin squares were selected because they reduce the influence of serial effects statistically, and because their power is concentrated on treatments. The treatment main effects, rate crossed with PCF, and their interaction were assigned within Ss. Latin square orders were assigned at random to Ss within each block.

Procedure

Practice Session

Acquisition of the tracking task involved a previously discussed pre-test session during which 24 Ss were trained separately to asymptote under conditions of steady illumination and distributed practice. The training consisted of rotary tracking of the disc on the turntable with the stylus. There was no feedback other than visual information to indicate whether the S was on or off the target.

Training to asymptote typically involved Ss reaching one plateau which occurred approximately one third of the time between start and asymptote, and involved a response measure which was

approximately one third of the response magnitude at asymptote. This procedure occupied between 10 and 25 minutes. To reduce possible carry-over effects due to fatigue, this practice session was given on a day prior to the test session. In general, the criterion for asymptote was defined as less than a one second change in response over five 22 second trials after the first plateau.

Test Session

Each S was tested separately during a 45 minute test session which was preceded by a three or four minute practice period on the pursuit rotor. Ss were seated at right angles to the direction of the incident light in order to eliminate glare from light reflected by the turntable. There were 13 treatment conditions. The first for each S was a control condition of steady illumination. The remaining 12 experimental conditions were combinations of four rates (4.9, 9.8, 23 Hz & fusion) and three PCFs (0.125, 0.25, & 0.50) presented in Latin square order. The dependent variable was the time on target in seconds averaged over three repeated measures of each set of treatment conditions. Ninety second rests separated treatment conditions.

Results

Log average data from Experiment I are presented in Table 8 of the appendix. The natural log transformation was made because it normalized the variances and because it facilitated later

Table 1

Analysis of Variance: Experiment I

Source	df	MS	F
Periods	11	0.022	1.06
Rows			
Blocks	1	0.510	
Orders	11	0.075	<1
Bl x Ord (error)	11	0.107	
R x C			
Bl x Per	11	0.023	
Ord x Per			
Treatments			
Rate	3	7.252	348.66**
PCF	2	5.279	253.79**
Rate x PCF	6	0.524	25.19**
L.S. Residual	110		
Bl X Per X Ord			
Bl x Treat	11	0.079	
Bl x L.S.R.	110		
Error	220	0.0208	
Total	287		

** $p < .01$

statistical controls applied to reduce inter-subject variability due to normal differences in motor control. These statistical controls took the form of a percentage transformation where log differences were taken between the control (steady) condition and each of the 12 experimental (flicker) conditions. These log differences are, in effect, error scores since they represent differences between steady and flicker conditions. Difference scores are presented in Table 9 of the appendix. Each entry in this table represents the log difference of the arithmetic mean of three repeated measures taken on each treatment from each subject. Actual computations involved logs being taken of the averages instead of averages of the logs, in order to obtain arithmetic means rather than geometric means. The data of Table 9 are organized to represent the basic two-block 12 x 12 Latin square design.

The results of the analysis of variance on these data are presented in Table 1. The period component or serial effect ($F = 1.06$, df 11/220) was not significant. Likewise the Latin square orders ($F < 1$) were not significant. The lack of statistical significance of these two components was the result of the co-ordination and integration of various experimental and statistical controls discussed in the methodology. This information virtually precludes the attribution of differences in treatments to such things as sequential and carry-over effects, and thus introduces greater confidence into the interpretation of the treatment main

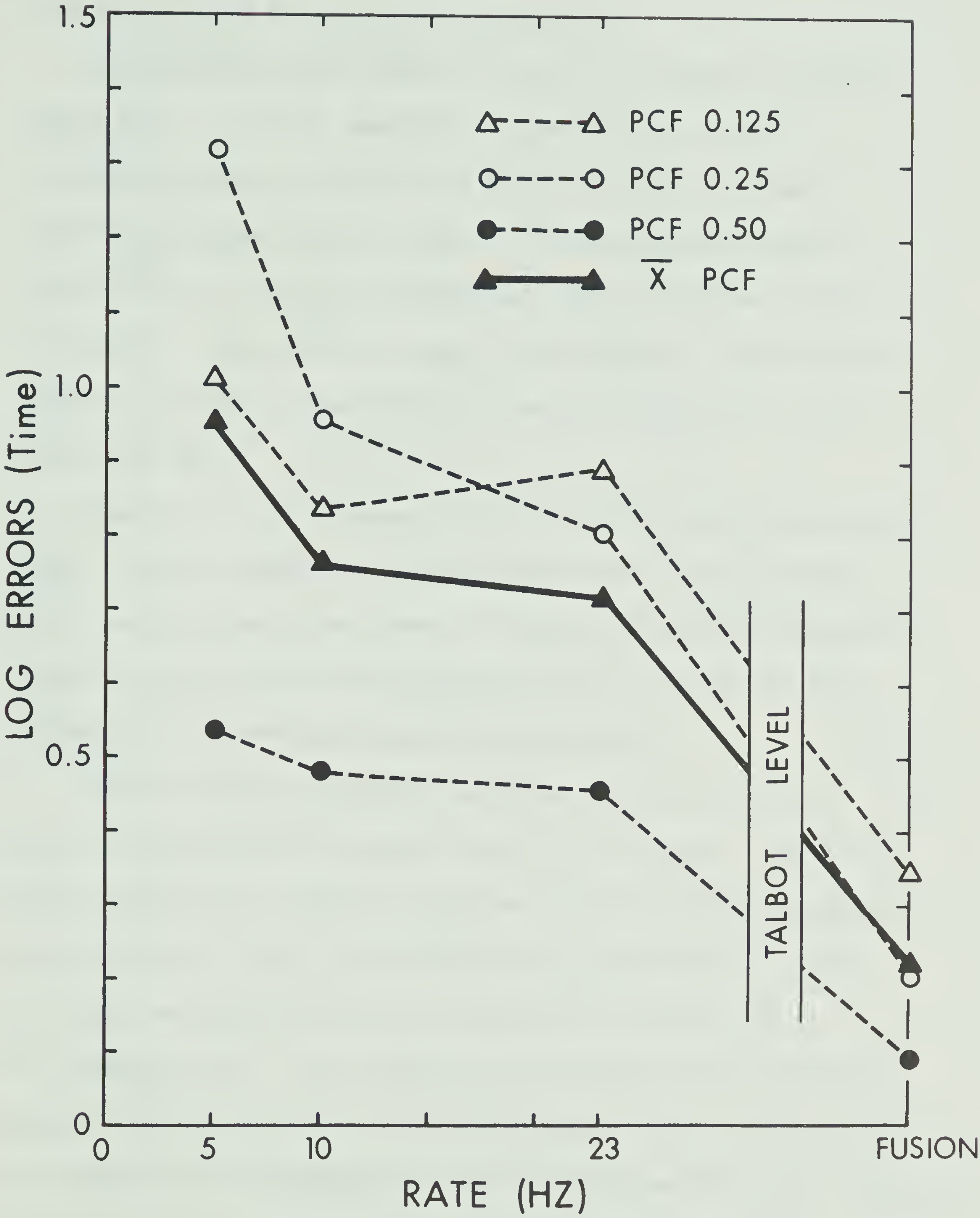


Figure 2: Log Error Motor Performance as a Function of Rate of Photic Intermittency for 0.125, 0.25, 0.50, and $\overline{X}$ PCF (MacDonald-Nelson, exp. I, 1969).

effects (rate and PCF) and their interaction.

Both treatment main effects of rate (F = 348.66, df 3/220) including 5, 10, 23 Hz, and fusion; and PCF (F = 253.79, df 2/220) including conditions of 0.125, 0.25 and 0.50 were significant beyond the 0.01 level. The interaction between rate and PCF (F = 25.19, df 6/220) was also significant to the 0.01 level. These results support the hypothesis that varying both rate and PCF is important for tracking efficiency in this particular task.

Figures 2, 3 and 4 respectively show the effect obtained when rate is varied, when PCF is varied below Talbot level, and when PCF is varied above Talbot level. Scheffé's multiple comparisons (Table 2) were run on various rates and PCFs to establish the reliability of the trends shown in these figures.

Figure 2 shows a generally declining trend in errors as rate of intermittency increases from 5 Hz to fusion. The first three comparisons in Table 2 indicate that the differences between 5 and 10 Hz (F = 68.15, df 1/220), and 10 and 23 Hz (F = 3.49, df 1/220) averaged over PCF are reliable (P = 0.01, 0.10, & 0.01 respectively). The reduced significance of the decline in errors from 10 Hz to 23 Hz for $\overline{X}$ PCF appears to be the result of a slightly rising trend between these rates under PCF 0.125. This rise in errors is not significant (comparison 9, Table 2).

Figure 3 shows a curvilinear trend in which errors averaged over subfusional rates are optimal at PCF 0.25. Graphical

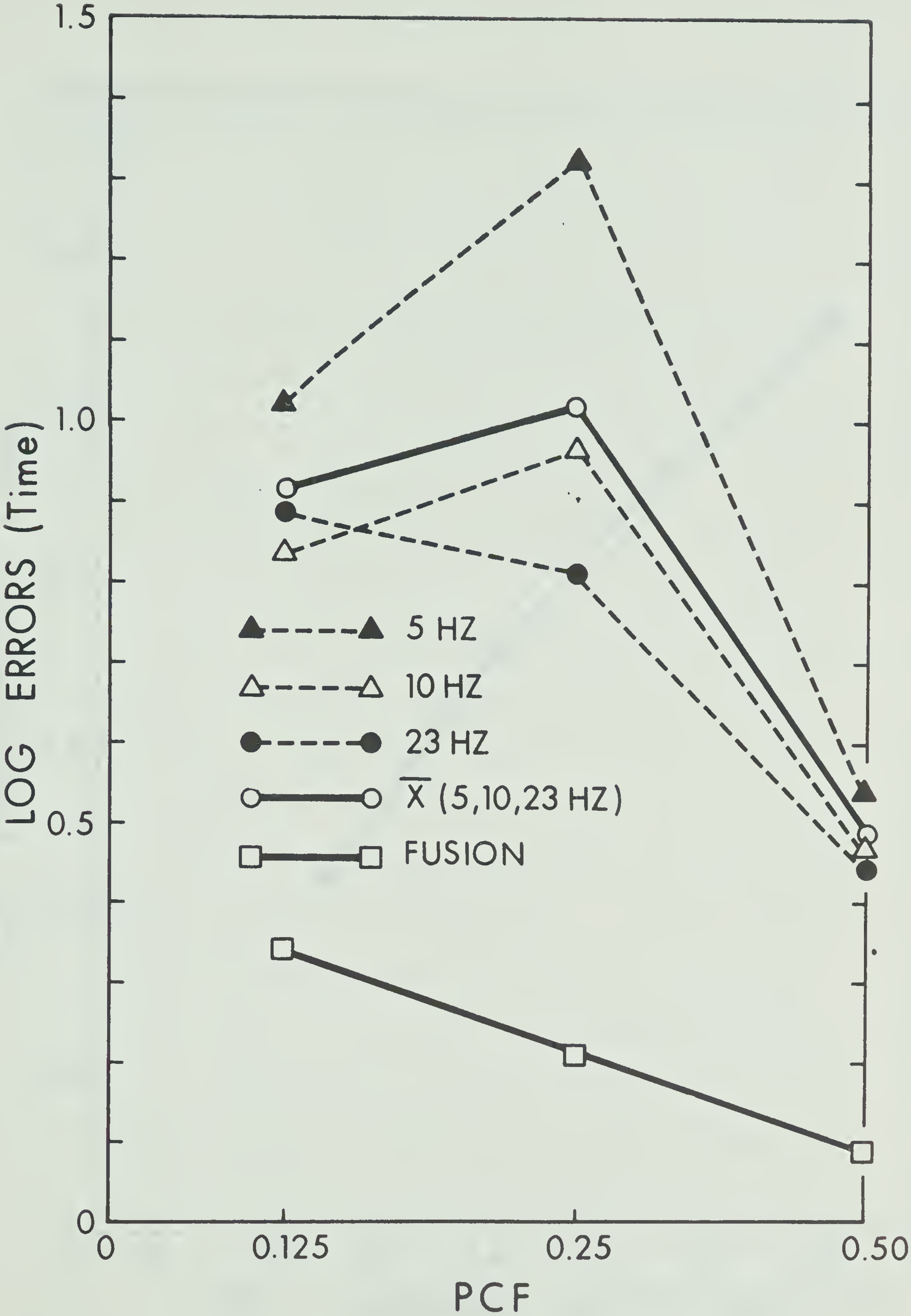


Figure 3: Log Error Motor Performance as a Function of PCF for 5, 10, 23 Hz, and Fusion (MacDonald-Nelson, exp. I, 1969).

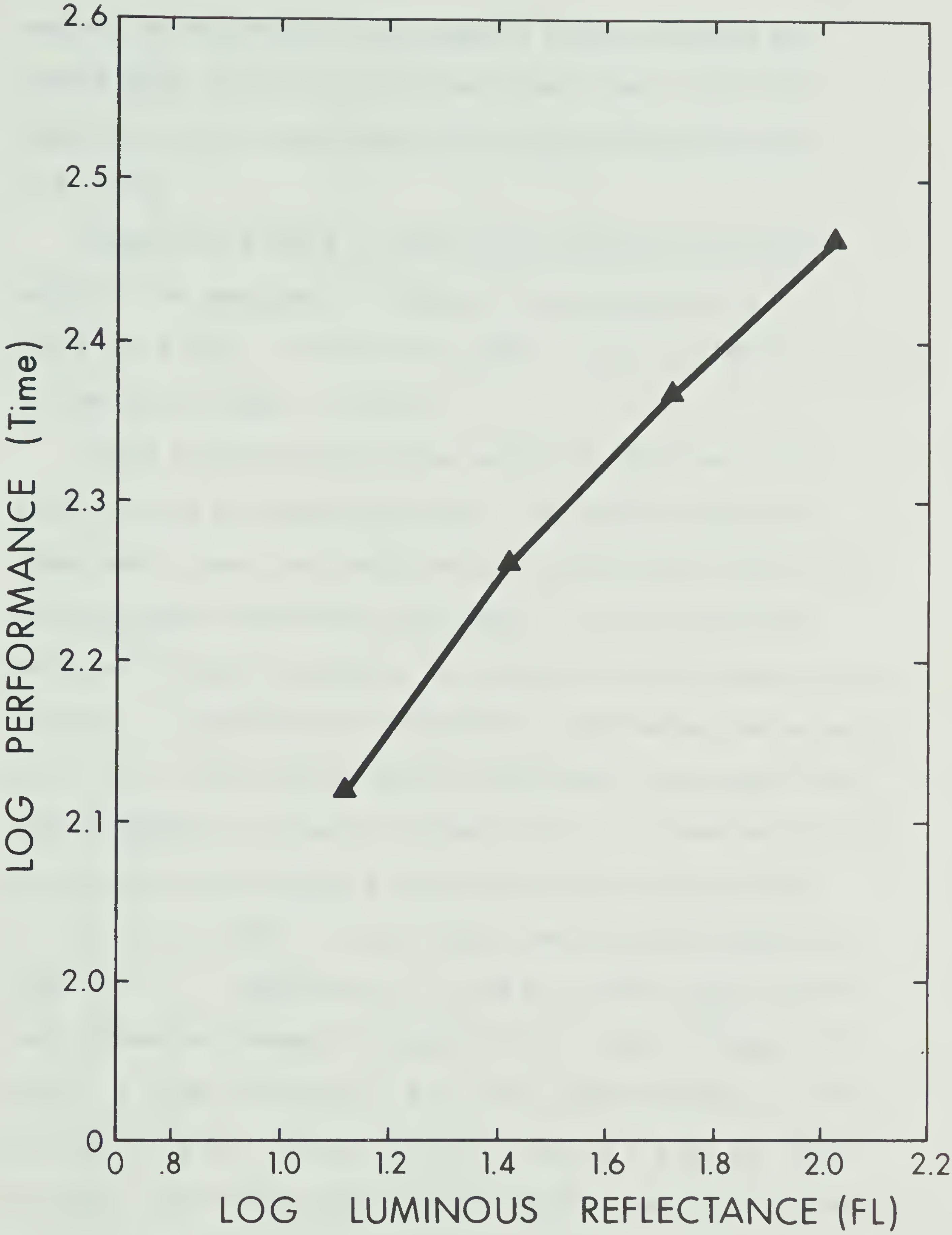
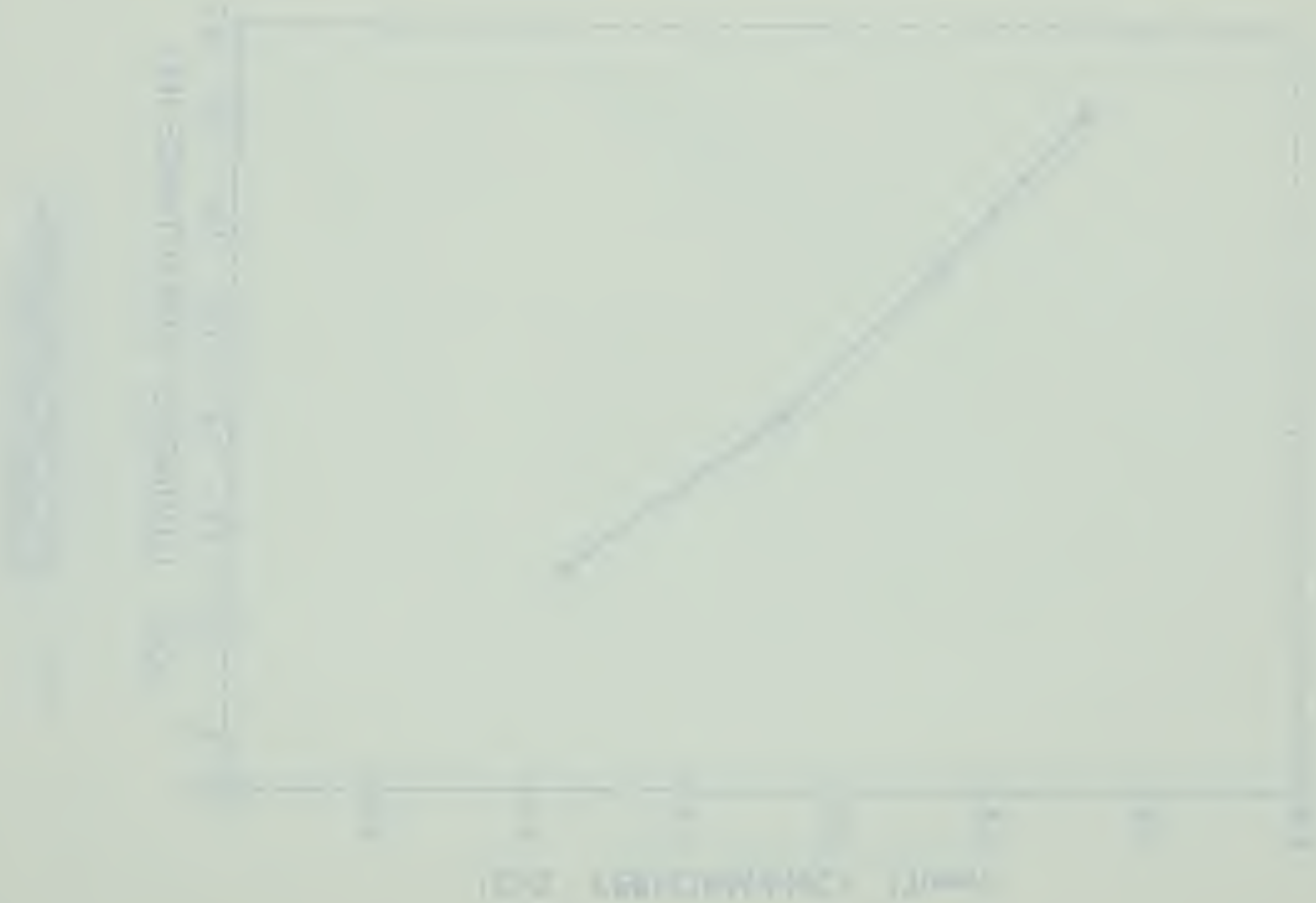


Figure 4: Log Motor Performance above Talbot Level as a Function of Log Luminous Reflectance (MacDonald-Nelson, exp. I, 1969).



analysis of this trend for the specific rates used shows this optimal point to exist only for the slower rates, 5 and 10 Hz. Higher rates show a declining trend in errors from PCF 0.125 to PCF 0.50.

Comparisons 4 and 5 in Table 2 show that the curvilinear nature of the mean curve in Figure 2 is also significant (PCF 0.25 > 0.125; $F = 28.18$, df 1/220; $P < 0.01$ and PCF 0.125 > 0.50; $F = 296.85$, df 1/220; $P < 0.01$).

Figure 4 describes the linear nature of the three fusion conditions and the steady condition. For certain theoretical comparisons, these four conditions can be considered controls for the subfusional experimental conditions. In this particular curve the ordinate is graduated in terms of log performance, not of log error. The abscissa is graduated in log luminous reflectance, not in PCF. This is statistically permissible since above Talbot level, brightness is directly related to PCF. A trend analysis on this curve (Table 3) shows a highly significant linear trend ($F = 74.32$, df 1/220; $P < 0.01$), but a non-significant quadratic trend ($F < 1$). Comparisons 6, 7, and 8 in Table 2 show significant differences between all points on this curve. (Steady > PCF 0.50, $F = 11.84$, df 1/220, $P < 0.01$; PCF 0.50 > PCF 0.25, $F = 6.92$, df 1/220, $P < 0.01$; and PCF 0.25 > PCF 0.125, $F = 4.83$, df 1/220; $P < 0.01$). The linear nature of this curve is important for later theorizing on relationships involving luminosity, visual acuity, and motor control.

Table 2

Scheffé's Multiple Comparisons on Differences Due to Rate and PCF

Comparison	Treatment Sums													Σa_i^2	D_i	D_i^2	A_i	S^2	F	P
	1	2	3	4	5	6	7	8	9	10	11	12	13							
	24.039	31.796	13.108	20.033	23.138	11.486	21.179	19.404	10.839	8.209	4.824	2.196	0.00							
(1) 1,2,3/4,5,6	1	1	1	-1	-1	-1	0	0	0	0	0	0	0	6	14.287	204.118	1.417	0.0208	68.15	0.01
(2) 4,5,6/7,8,9	0	0	0	1	1	1	-1	-1	-1	0	0	0	0	6	3.235	10.465	0.073	0.0208	3.49	0.10
(3)7,8,9/10,11,12	0	0	0	0	0	0	1	1	1	-1	-1	-1	0	6	36.193	1309.933	9.097	0.0208	437.34	0.01
(4) 1,4,7/2,5,8	1	-1	0	1	-1	0	1	-1	0	0	0	0	0	6	9.187	84.401	0.586	0.0208	28.18	0.01
(5) 1,4,7/3,6,9	1	0	-1	1	0	-1	1	0	-1	0	0	0	0	6	29.818	889.113	6.174	0.0208	296.85	0.01
(6) 10/11	0	0	0	0	0	0	0	0	0	1	-1	0	0	2	3.385	11.458	0.239	0.0208	11.48	0.01
(7) 11/12	0	0	0	0	0	0	0	0	0	0	1	-1	0	2	2.628	6.096	0.144	0.0208	6.92	0.01
(8) 12/13	0	0	0	0	0	0	0	0	0	0	0	1	-1	2	2.196	4.822	0.100	0.0208	4.83	0.05
(9) 4/7	0	0	0	1	0	0	-1	0	0	0	0	0	0	2	1.146	1.323	0.0275	0.0208	<1	N.S.

Table 3

Trend Analysis on Motor Performance above

Talbot Level as a Function of Log Luminous Reflectance

PCF	Log Lum. Ref.	Σ Log Perform.	Linear Coefficients		Quadratic Coefficients	
0.125	1.12	50.832	-3	-152.496	1	50.832
0.25	1.42	54.216	-1	- 54.216	-1	-54.216
0.50	1.72	56.832	1	56.832	-1	-56.832
1.00	2.02	59.040	3	233.952	1	59.040
Σ				27.240		1.176

Source	A	df	S^2	F
Linear	$\frac{27.24^2}{24 \times 20} = 1.5458$	1	0.0208	74.32**
Quadratic	$\frac{1.176^2}{24 \times 20} = 0.0029$	1	0.0208	<1

** $p < .01$

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[illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Experiment No. II

Experiment II was designed to investigate differential effects of wavelength on motor performance under stimulus conditions which produced the greatest decrement in the dependent variable, i.e. 5 Hz and 0.25 PCF. Although no specific predictions were made, the five wavebands were selected in an attempt to relate the phenomenon of reduced motor adjustment under flicker, to part spectrum variables controlling hue shift and color bleaching as studied by Ball and Bartley (1965). The design and controls of this experiment are very similar to those of the first experiment.

Subjects

Ten Ss were selected from the same population used in Experiment I. The same selective controls were applied.

Experimental and Statistical Controls

Experimental and statistical controls were, with two exceptions, identical to those in Experiment I. The first exception was that each intermittently presented color was compared with its own steady control. Log differences were taken between each experimental condition and its corresponding control. The second control involved four repeated measures under each treatment condition, the first of which was not included in the average and served only as a period of adaptation to that particular color. This control was introduced to compensate for low scores commonly found on the first of three repeated measures taken for various colors during the training session.

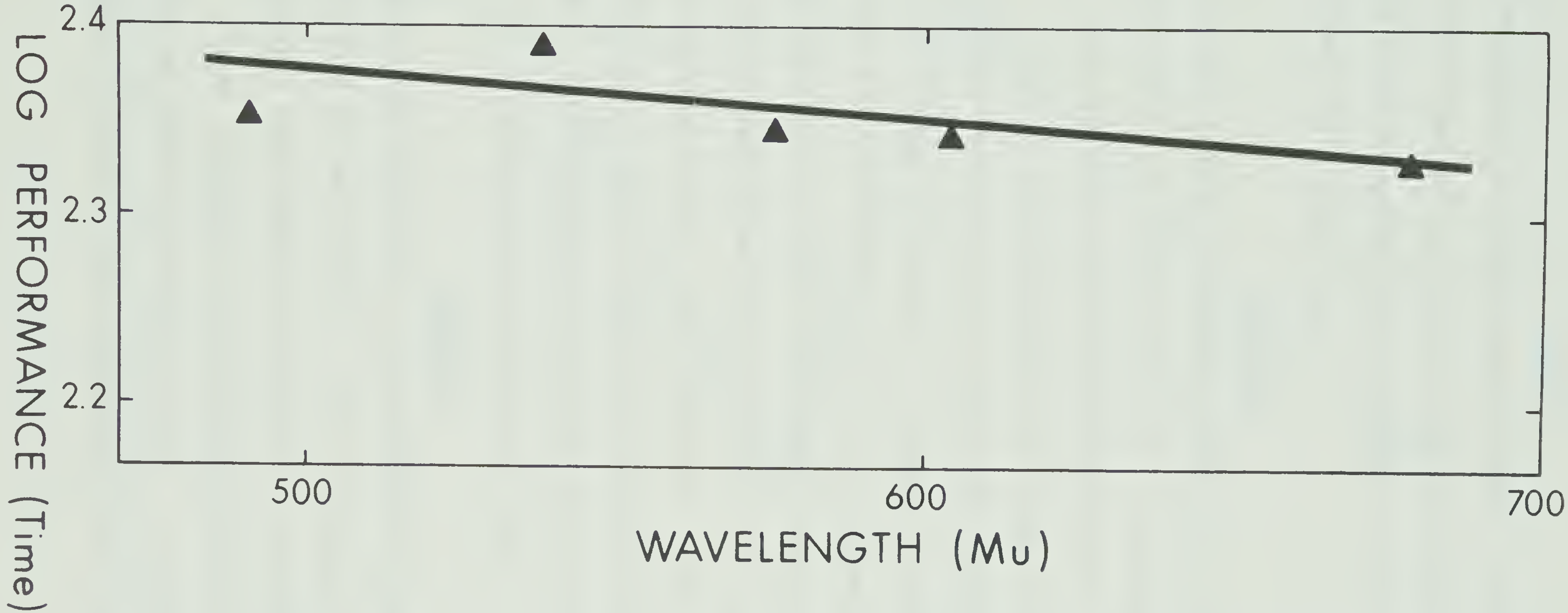

Figure 5: Log Motor Performance for Continuous Photic Stimulation as a Function of Wavelength (MacDonald-Nelson, exp. II, 1969).

Design

Two repeated 5 x 5 Latin squares (Table 7, Appendix) were blocked on the same variable used in the first experiment. Treatments (the five colors) were assigned at random to Latin square orders within each block.

Procedure

Ten Ss were trained to asymptote under full spectrum illumination during a pre-test session as in Experiment I. At the end of the session, scores were taken under 5 Hz and 0.25 PCF in order to block Ss on percentage use of visual information. Various practice trials were also given under different colors at both 5 Hz and steady illumination. Procedure during the actual test was also similar to that of the first experiment. Each S was tested separately on eight trials under each of five colors. The eight trials were broken into two sets of four which were separated by two-minute rests. The first set of four involved steady illumination and the second set involved flicker at 5 Hz and 0.25 PCF. The dependent variable was time on target averaged over the last three measures in each set of four.

Results

The data from Experiment II are presented in natural log form in Table 10 of the appendix. Table 10 Column A shows log steady (control) performance as a function of wavelength averaged over Ss. Figure 5 suggests that performance under steady illumination does not vary from filter to filter. A slight decrease in performance from the shorter wavelengths to the longer ones is

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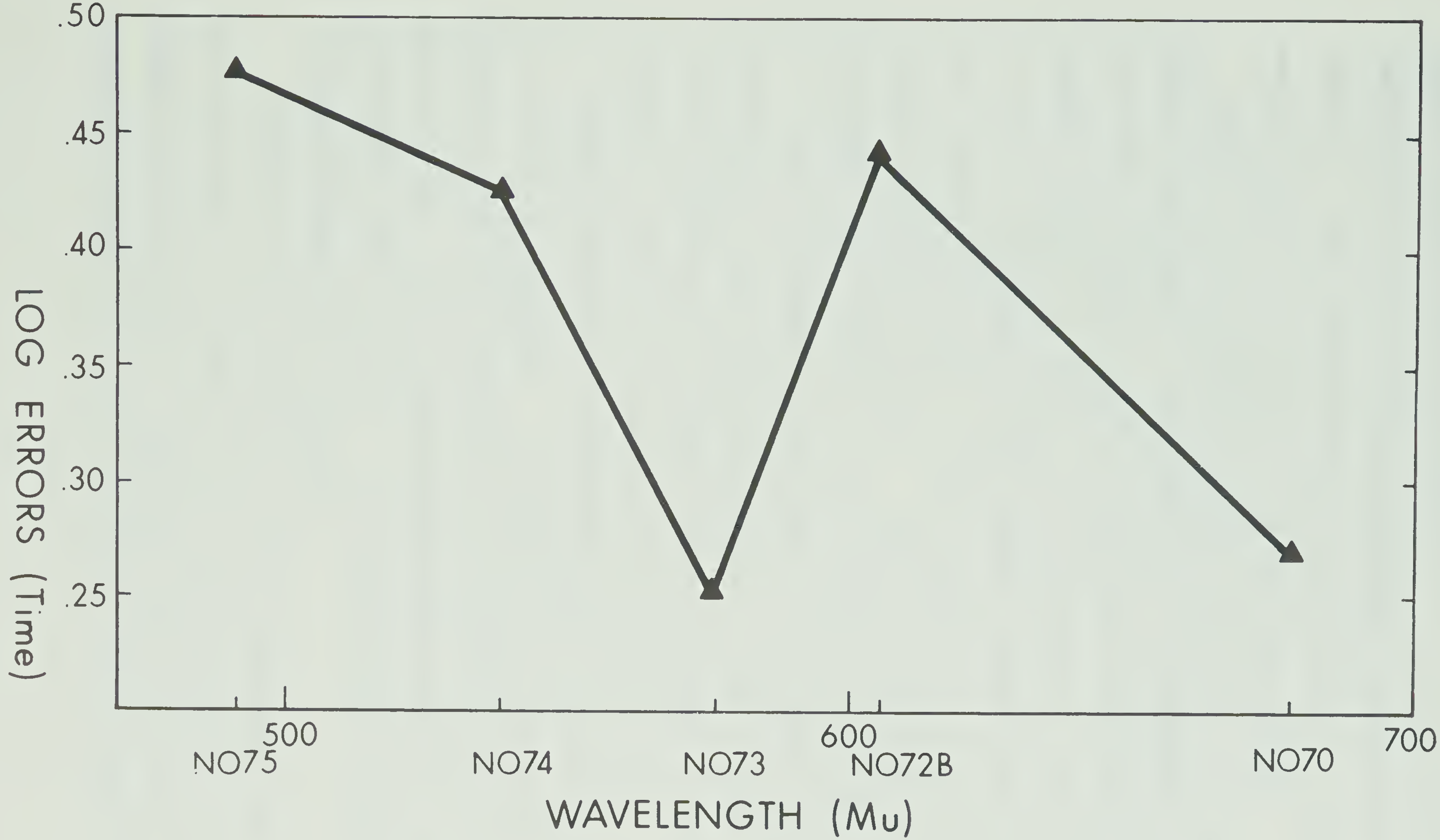

Figure 6: Log Error Motor Performance under 5 Hz and 0.25 PCF as a Function of Wavelength (MacDonald-Nelson, exp. II, 1969).

apparent, but both the linear component ($F < 1$) and the quadratic component ($F = 1.94$, df 1/24) were determined to be non-significant (Table 4). These results indicated that differences in luminosity were well-controlled by the use of neutral density filters.

Table 11 of the appendix represents the blocked Latin square design of Experiment II. Each cell entry is constituted by the log difference between flicker and steady under that particular treatment condition for each S. As in Experiment I, each entry is the log of the average of three repeated measures under the same set of treatment conditions. Table 5 presents the analysis of variance of the data in Table 11. Here, as in Experiment I, both the periods (serial effect, $F = 2.05$, df 4/24) and the orders ($F = 1.26$, df 4/24) were not significant. The treatment (color) main effect was again highly significant ($F = 12.56$, df 4/24; $P < 0.01$) indicating that different colors are important in producing variations in tracking efficiency in this particular task.

Figure 6 shows errors in performance under 5 Hz and 0.25 PCF as a function of wavelength. The shape of this curve is very similar to that of the desaturation curve obtained by Ball and Bartley (1965). Errors decrease between 490 mμ and 575 mμ, and also between 610 mμ and 680 mμ. An increasing trend in errors is apparent between 575 mμ and 610 mμ.

Scheffé's multiple comparisons (Table 6) were used to test the significance of the shape of this curve by evaluating differences between maxima and minima. Comparisons 1 and 2 show non-significant differences between the scores obtained with filters numbered 70 & 73;

Table 4

Trend Analysis of Control (Steady) Data

as a Function of Wavelength

Filter	Σ Log Perform.	$\overline{X}$	Linear Coefficients		Quadratic Coefficients	
70	23.271	2.33	-2	-46.542	2	46.542
72B	23.424	2.34	-1	-23.424	-1	-23.424
73	23.450	2.35	0	0	-2	-46.900
74	23.851	2.39	1	23.851	-1	-23.851
75	23.523	2.35	2	47.046	2	47.046
Σ				0.931		1.563

	A	df	S^2	F
Linear	$\frac{0.931^2}{10\text{x}10} = 0.008649$	1	0.00895	<1
Quadratic	$\frac{1.563^2}{10\text{x}14} = 0.01735$	1	0.00895	1.94

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Table 5

Analysis of Variance: Experiment II

Source	df	MS	F
Periods	4	0.018	2.05
Rows			
Blocks	1	1.102	
Orders	4	0.067	1.26
Bl x Ord	4	0.053	
R x C			
Bl x Per	4	0.009	
Ord x Per			
Treatments	4	0.112	12.56**
L.S. Residual	12		
Bl x Per x Ord			
Bl x Treat	4	0.007	
Bl x L.S.R.	12		
Error	24	0.00895	
Total	49		

**p<.01

and 72B & 74 respectively ($F < 1$; $F < 1$). Comparison 3 however shows that the combination of filters numbered 74 & 72B is different from the combination numbered 73 & 70 ($F = 34.31$, df 1/24; $P < 0.01$). Comparison 5 tests the difference between filters numbered 75 & 74. This difference ($F = 1.58$, df 1/24) is significant only at the 0.25 level.

Table 6

Scheffé's Multiple Comparisons on Differences

Due to Wavelength

Comparison	Treatment Sums	Σa_i^2	D_i	D_i^2	A_i	S^2	F
	1 2 3 4 5						
	2.699 4.445 2.512 4.271 4.803						
(1) 2/4	0 1 0 1 0	2	0.174	0.0303	0.0015	0.00895	<1
(2) 1/3	1 0 -1 0 0	2	0.187	0.0349	0.0017	0.00895	<1
(3) 2,4/1,3	-1 1 -1 1 0	4	3.505	12.2850	0.3071	0.00895	34.31**
(4) 5/4	0 0 0 -1 1	2	0.532	0.2830	0.0142	0.00895	1.58*

* p <0.25
** p <0.01

Discussion

Interpretation of the Results Within the Alternation of Response Theory

Flicker Study

In general, tracking efficiency in the specific motor task employed was reduced in a manner commensurate with the expectations of the alternation of response theory. Optimal[4] decline in visual-motor coordination occurred under the same conditions of intermittency (5 Hz & 0.25 PCF) which have produced changes in other visual processes, especially those involving brightness and acuity.

Although the alternation of response theory predicts the results accurately, it is difficult to determine to what extent the results confirm the theory. The lack of statistical significance of the period and order components validates the interpretation of the treatment effects, but the theoretical significance of these effects must be evaluated carefully with respect to the alternation theory. The significance of the main effects (rate and PCF) is important for relating the present data to other data collected on flicker phenomena. However, the fact that rate and PCF interact is critical for explanations within the alternation of response theory.

The interaction of rate with PCF can be interpreted both statistically and theoretically. At a superficial level of analysis, the results of both approaches are identical; rate and

[illegible]

PCF are interdependent. At a more refined level, it becomes apparent that these modes of analysis represent interpretation of the results along two orthogonal dimensions, one having neurophysiological implications for the alternation of response theory, the other being purely an integration of discrete physical dimensions of stimulus intermittency.

A theoretical account suggests that this interaction represents a set of physical concomitants which provide for simultaneous discharge and recovery of an optimal number of channels in the optic pathway. The temporal pattern of neural discharge and the recovery time of the fibers are the neurophysiological consequences of particular physical parameters of pulse duration, and the inter-stimulus interval. Within the design of the experiment,the combined effect of these physical parameters is specified by the interaction of rate with PCF, but rate and PCF as separate concepts are not temporal analogues of stimulus duration and the inter-stimulus interval.

The significance of rate and PCF as separate components of this interaction is of limited value to the alternation of response theory. Rate and PCF data may be used to fit curves and approximate data collected under similar physical conditions of stimulation, but theoretical extensions to neural activity on the basis of these data should be purely speculative and should not result in specific empirical predictions within the alternation theory. Fry (1965) has attempted to clarify the relationship between the physical conditions of stimulation and temporal aspects of the

improvements in visual acuity[5] as described by Bartley, Nelson, and Soules (1963), and Bourassa and Bartley (1965). Both the motor performance and visual acuity curves correlate well with the curves showing brightness changes under intermittent illumination. Maximum disruption in both these processes is found at the pulse rates producing the greatest brightness. As pulse rate is increased, both brightness enhancement and motor errors are reduced.

Rates below 5 Hz were not tested to preclude the simultaneous operation of dilation and constriction mechanisms involved in pupillary response, which is thought to produce visual discomfort at low rates of intermittency (Bartley, 1942). Low rates also result in the perception of a series of discrete flashes rather than a continuous undulating train of stimulation, which would complicate the interpretation of results. It is unlikely that pupillary diameter influenced the results of the present study since brightness changes caused by photic intermittency have been found with both artificial and natural pupils. Pupillary response was not controlled in the present study since the use of an artificial pupil would reduce the effective level of illumination to a point at which brightness enhancement would not be expected to occur. The importance of the contributions expected from testing low rates did not warrant the use of the necessary optical and postural controls. However, it is expected that for rates below 5 Hz, errors on the tracking task would decrease since the pulse length would be long enough to allow the temporal distribution of neural activity in the pathway. This activity would carry over to the inter-pulse period

and consequently reduce bunching in the system.

The similar shapes of brightness, acuity, and motor curves for rate suggest the operation of a factor common to all these processes. Analysis of PCF curves further substantiates this notion.

Interpretation of the PCF curves (Figures 3 & 4) is straightforward. At 5 and 10 Hz, optimal reduction in tracking efficiency occurs under PCF 0.25. The higher rates of intermittency show a decrease in errors as PCF increases. This trend appears to become linear when rate reaches CFF. The shape of these curves both above and below Talbot level can be explained by the alternation theory. The shape of the motor curves below Talbot level closely approximates the shapes of brightness and acuity curves under flicker (Bartley, Nelson, and Soules, 1963; Bourassa and Bartley, 1965; Rabelo and Grüsser, 1961). Further supporting evidence that acuity and motor performance are related in the present study is demonstrated by the increase in performance above Talbot level as PCF increases (Figure 4). The abscissa of this figure was plotted in luminosity rather than in PCF for the specific purpose of making comparisons with visual acuity curves, for example those of Hecht (1928) and König (1897),[6] which show similar increasing trends as a function of increasing intensity of illumination. Comparisons between visual acuity curves and the motor performance curve in Figure 4 are justified since above Talbot level the visual system analyses intermittent input as if it were continuously presented. At fusion, changes in PCF are dealt with by the visual system in the

same manner as are changes in luminosity.

While the postulation of a factor common to brightness, acuity, and motor processes seems plausible on the basis of the data discussed, the unconditional acceptance of such an idea might result in a misconception which could impede progress in the understanding of the visual system. Bartley (1968) for example, proposed different spatial processes for brightness and acuity which will be discussed later. It should not be assumed that an underlying visual process, whether it be better understood as a psychological process or as a physiological process, necessarily relates to brightness in the same manner as it relates to acuity. Interpretation of the color data within the alternation of response theory clarifies this perspective.

Color Study

Ball and Bartley (1965) plotted a decreasing trend in brightness from the shorter wavelengths to the longer ones for 6 PCFs flickering at 9.8 Hz. Overlooking the obvious relationship to desaturation, an hypothetical relationship between brightness and acuity which arises from the results of the flicker study could be modified to explain variations in tracking efficiency in most areas of the spectrum, the exception being the area between 600 mμ and 640 mμ where tracking errors and desaturation both increase.

It is more inviting to relate the color curve (Figure 6) and the desaturation curve (Ball and Bartley, 1965) to a single underlying visual mechanism; however, the congruity of these two curves is difficult to assess. The use of a prism monochrometer

by Ball and Bartley provided for better control of the widths of pass-bands in different parts of the spectrum than did the use of Wratten filters in the present study. Pass-bands of these filters are relatively wide and vary inconsistently in both width and in luminous transmittance at different wavelengths (Kodak Wratten Catalogue, 1962). Furthermore, Ball and Bartley collected only ordinal data on the dependent variable (desaturation), whereas in the present study ratio data were collected on error motor performance. Since any comparison between the two curves must necessarily occur on an ordinal basis, its specificity would be reduced.

In general, the fact that the motor data fit the desaturation curve better than they fit the brightness curve, seems to be inconsistent with any proposed relationship between brightness and acuity. The neurophysiological basis for spatially different mechanisms of brightness and color coding is well established. The work of MacNichol (1964) on color processing, and of DeValois (in Neff, 1965) on broad-band and spectrally-opponent cells in the lateral geniculate bodies complicates the attribution of color, brightness, and acuity phenomena to a reduced number of underlying variables.

In view of these inconsistencies, the proposal of any relationship involving color, acuity, and brightness, must be made conservatively. With minimal direct empirical evidence relating these three variables, and with these inconsistencies in mind, an explanation is presented which relates color, acuity, and brightness at a theoretical level.

Some Speculative Relationships Between Temporal Factors Involved in Color Coding and Spatial Factors Involved in Visual Acuity

The relationship between desaturation (Ball and Bartley, 1965) and tracking performance (Figure 6) seems superficially coincidental since no immediate connection is made between the two, or between acuity and desaturation. An explanation based on empirically grounded color coding phenomena is presented to account for this relationship.

The lack of correspondence between existing neurophysiological evidence of visual processes (most of which has been collected in animal studies) and experiential data (all of which involves subjective human response) reduces this explanation to a purely speculative level. Confidence in this explanation is limited by the validity of two assumptions, the first being that the wave form of the visually evoked potential (VEP) reflects qualitative dimensions of experiential color, and the second being that the times of critical components of the VEP are related to times needed to perceive various colors.[7]

Within the physical sciences, relationships between wavelength and parameters thought to be important for acuity (focal length, intensity, etc.) have been well established, but the relationship between psychological aspects of color and acuity is not well documented. Koffka and Harrower (1932) found visual acuity to be better with targets seen as red, white, or yellow, than with targets

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seen as blue or black. Bartley (1968, p. 158) accounted for this by relating surface associations to color. He noted that red, yellow, and white appear "hard" or tactile whereas blue appears "soft" and is more difficult to localize in space. In Experiment II, reduced ability to localize certain colored surfaces in space is associated with reduced ability to perceive abrupt changes in color gradients which form the boundary between the target to be tracked and the white surround of the turntable. The data of Ball and Bartley (1965) showed blue to be most desaturated under stimulus intermittency, whereas red and yellow remained saturated. Since saturated colors are generally considered "hard" and desaturated colors considered "soft" the possibility of an interesting relationship between desaturation, color, and acuity arises.

The theoretical delineation of this relationship involves the integration of temporal patterns of neural discharge associated with color coding, with spatial patterns of activity proposed by Bartley (1968) to account for the reduction in acuity under flicker.

Bartley differentiated between longitudinal activity in the pathway and transverse activity at various stations along it, (e.g. the retina[8] and lateral geniculate bodies). Visual acuity was postulated as a sensory effect which was dependent upon certain neural processes called contour processes. These processes were thought to involve the lateral transmission of information across various channels in the visual system. Inferences from the work of Fry (1934) and Werner (1935) led to the idea that such processes take certain measurable amounts of time to reach completion.

Intermittent photic input bunches longitudinal activity, and in so doing does not allow sufficient time for the lateral processes to reach completion, thus diminishing visual acuity.

Recently acquired information on temporal patterns of activity involved in color coding forms the empirical basis for the relationship between color and acuity. König (1897) concluded that information from the longer wavelengths is conducted by fibers which synapse only with cones, whereas information from the short end of the spectrum is carried by fibers which synapse with both rods and cones. Later Chang (1950) demonstrated that red is coded more quickly by the system than is blue. Madsen and Lennox (1955)[9] showed that various types of spectral pass-bands evoked different types of activity at the visual cortex.

Shipley, Jones, and Fry (1966) found the wave forms of VEPs (VEOGs)[10] to be different for pass-bands with dominant wavelengths at 680 nm (red), 575 nm (yellow), 520 nm (green) and 400 nm (violet).[11,12] Shipley et al. noted that this wavelength specificity was consistent with the idea that the neural bases of the chromaticity and luminosity mechanisms are relatively independent. This gives rise to a possible integration, again at the speculative level, of Bartley's notions of longitudinal and contour processes with the neurophysiological work of MacNichol (1964) and De Valois (1965) mentioned previously.

Although the wave forms of these VEPs are complex, their temporal relationship to Bartley's contour processes is easily explained in terms of differences in implicit times.[13] The implicit times of

red ($\doteq$180 ms) and yellow ($\doteq$200 ms) are shorter than those of green ($\doteq$300 ms) and violet ($\doteq$250 ms).[14] Under intermittency conditions of 5 Hz (i.e. 200 ms cycles), red and yellow are effectively processed by the system since the components of their VEPs important for color coding can be maintained over a train of pulses. Green and blue will not be entirely coded within the duration of one cycle (200 ms). Disruptions in temporal patterns of information for these colors would begin with the onset of the second pulse in the train. Information from only the quicker fibers conducting impulses from green receptor elements, for example, could be coded by the contour processes prior to the onset of the second cycle. After several cycles, residual information from preceding cycles would be summated with information coded by quicker fibers in succeeding cycles, thus producing transformations in the complexity of the wave form.

The population of red receptor elements is greater than that of blue receptor elements (Polyak, 1957). The fact that better acuity is associated with red than with blue may be due either to the summated effect of the larger number of red receptor elements in the human retina, or it may be entirely a probabilistic consequence of the greater distribution of quicker firing fibers associated with red receptor elements.

This hypothesis can also account for hue shifts and differences in desaturation produced by stimulus intermittency. If discharge times of various fibers are distributed in some specifiable manner

(e.g. normally, binomially, etc.), when a green light is presented at 5 Hz, information from only a certain percentage of the fibers synapsing with green receptor elements will be transmitted quickly enough to be processed by the visual system in the normal manner. Information conducted by the rest of these fibers in any cycle is integrated with information from succeeding cycles in various temporal arrangements. These patterns result in the neurophysiological production of a spectrum of hues, green being the strongest. The summation of energy distributions producing these hues might result in something resembling full spectrum stimulation, but since much of the green information is coded normally under 5 Hz, and the generation of information for hues other than green merely reflects inadequacies of the visual system to deal with intermittent afference, green would remain predominant. The final sensory end result under 5 Hz would be a desaturated green.

The integration of hue shift phenomena with desaturation is direct. Ball and Bartley (1965) would expect the sensory end result of green to be a desaturated yellowish-green since direction of hue shift in the green area is towards the longer wavelengths. The explanation for this shift in hue is that green photic intermittency produces a negatively skewed distribution of neurophysiological hue components which summate about a modal yellowish-green. Blue, the point of greatest saturation under intermittency, would result in a normal distribution of hues which summate about blue. A Fourier analysis of the VEPs of Shipley

_et al_. might provide empirical substantiation for this explanation.

Empirical studies of the relationship between color, acuity, and desaturation are almost totally lacking. Shipley, Jones, and Fry (1966) state:

> It is clear that a great deal of work must be done before the monochromatic VEOG is fully described. Discussions as to the meaning of this or that wavelet, or the uniqueness of some wavelengths, or the absolute amplitudes or culmination times, or of the unresponsiveness of the deuteronomalous observer, intriguing as they may be--would be gratuitous at this time . . . . . .

While the tone of this explanation has reflected the hypothetical nature of the relationship, it nevertheless gives rise to some interesting theoretical predictions which, upon testing, might provide information which is invaluable to the investigation of temporal processing in the visual modality. Color studies involving both dynamic and static visual acuity under flicker are suggested as a logical continuation of the present study.

Summary and Conclusion

This work is the first to relate the alternation of response theory to motor processes. Perceptual-motor tracking efficiency under intermittent photic stimulation was successfully predicted by the alternation theory. Previous investigations of motor control under flicker varied rate of photic intermittency, but neglected to study a range of relevant PCFs. The physical interaction of rate with PCF provides a temporal analogue to the neurophysiological interaction between patterns of discharge and recovery of channels in the visual system.

In Experiment I, tracking efficiency on a pursuit rotor task was found to be maximally reduced under the same conditions of intermittency (5 Hz and 0.25 PCF) which have previously been shown to produce maximal disruption[15] in visual acuity and brightness processes. In Experiment II, the phenomenon of reduced tracking efficiency under 5 Hz and 0.25 PCF was found to be wavelength-specific. It appears to be related to phenomenal desaturation which also occurs under these conditions of stimulus intermittency. Tracking errors occur to a greater extent with desaturated colors (blue and green) than they do with colors which remain saturated under flicker (red and yellow). The results of this color study were discussed in terms of temporal factors involved in color coding and visual acuity.

This study has introduced a method for determining the type of visual information which is important in perceptual-motor tracking. The extent to which visual information is important

in the particular tracking task used was determined by the effectiveness of the temporal manipulation of photic input which was ascertained by comparing differences in tracking data collected under steady illumination with those collected under intermittent illumination.

This method is of practical use in situations where it is helpful to reduce a person's dependence upon visual information in order to correct a behavioral malfunction. It could be of considerable use in physical education where the reduction of visual information facilitates the better use of kinesthetic and other non-visual cues at some stages in the acquisition of various motor skills.

The flicker method might also be employed in various therapeutical situations, for example in the training of cerebral palsied children, where current methods rely heavily upon their making the best use of inadequate visual information.

Although the discussion of the present research alludes to underlying neurophysiological and biochemical explanations, for the present, the best predictor of tracking efficiency under flicker is the alternation of response theory which relates it somewhat tenuously, but with promise, to visual acuity.

Footnotes

1 It is interesting to note that many other descriptive techniques used in experimental psychology, for example statistics, were developed first within agronomy.

2 Attempts to integrate space and time have been more successful within classical mechanics and Einsteinian physics.

3 The pulse-to-cycle fraction is the proportion of time that the light is on during the cycle.

4 The term "optimal" is appropriate only in as much as rate is a fixed and not a random component of the experimental design.

5 Most of the data presented to relate acuity to motor processes are relevant to static acuity (the resolution of fixed targets). The present study involved dynamic visual acuity which may involve separate visual processes. Ludvigh and Miller (1953) reported that not all _S_s with good static acuity demonstrated good dynamic acuity, and _vice versa_. This notion further reduces the specificity with which comparisons between the acuity and motor data should be made.

6 König's (1897) data were re-plotted by Hecht (1928) in millilamberts.

7 Although direct empirical evidence for these ideas is minimal, White and Eason (1966) demonstrated that brightness is related to the amplitude of the VEP. Their attempts to relate hue to the wave form and saturation to wave complexity were not entirely successful.

8 Lateral transmission of information in the retina is thought to occur via the amacrine and horizontal cells.

9 The data of Madsen and Lennox (1955) were collected from cats. The fact that cats do not have good color vision is not so important in the light of later evidence collected by Shipley _et al_. (1966) on human cortical evoked potentials.

10 (Visually Evoked Occipitogram). Shipley _et al_. (1966) discuss the differences between VEOGs and VEPs, etc.

11 Shipley _et al_. (1966) measured wavelength in nanometers (nm), not millimicrons (mμ). One of three observers was deuteranomalous.

12 Dustman and Beck (1965) found that inter-subject differences in wave form were significant whereas intra-subject differences (within _S_s, over time) were not.

13 The implicit time is the time from the onset of the stimulus to the peak of the response. Although it does not represent all the complexities in the wave form which are involved in color coding, this concept is useful for explanatory purposes.

14 The implicit times become shorter with increases in intensity of illumination. This is expected from other work relating the magnitude of the stimulus to the magnitude and latency of the response. The suggestion has been made that due to the long implicit times, the explanation may not work for flicker at low intensities. This is consistent with the explanation since neither brightness enhancement nor color shifts occur at the lower intensities.

15 The term "disruption" refers appropriately to acuity processes. There is some discussion as to whether enhanced brightness is disruptive or not.

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Appendix

Log Transformed Data:

Experiments I and II

Table 7

Latin Square Orders

Experiment I (12 x 12)

CDKJGAEHILFB
BFIHLGACDEKJ
JKDCELGBFAIH
LBHAIKFGCDJE
EJCGDIKLBFHA
HIFBAELJKGDC
GCJEKFDAHIBL
FALIBCHDEJGK
ILAFHJBKGCED
AHBLFDIEJKCG
DEGKCHJILBAF
KGEDJBCFAHLI

Experiment II (5 x 5)

AEBDC
EBDCA
DCAEB
CAEBD
BDCAE

Table 8

Log Transformed Data: Experiment I

	Ss	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}
Block 1	1	2.515	1.3888	0.97833	1.7504	1.9242	1.7054	1.909	1.7102	1.5967	1.863	2.2375	2.3552	2.4604
	2	2.5069	1.4359	1.0152	1.5026	1.2198	1.0531	2.1545	1.6589	1.4793	2.0242	1.8779	2.3062	2.3982
	3	2.6283	1.6114	1.1303	1.8911	1.8421	1.687	1.9291	1.4142	1.7305	1.8966	2.1167	2.3918	2.5107
	4	2.5626	1.8331	1.1745	1.912	1.7352	1.2316	1.8692	1.7923	1.6312	1.9544	2.1868	2.3263	2.3681
	5	2.6769	1.2139	1.1632	2.2663	1.6396	1.744	2.346	1.6371	2.1163	2.2364	2.3286	2.4841	2.6071
	6	2.2364	1.208	0.78694	1.3601	1.4493	1.2287	1.909	1.0908	1.4989	1.6101	1.789	1.9203	2.1183
	7	2.5239	1.2509	1.0555	1.7084	1.5672	1.3191	2.151	1.7364	1.9169	2.0273	2.2875	2.4242	2.4777
	8	2.6017	1.7257	1.1673	2.3746	2.0145	1.84	2.337	1.8132	2.0158	2.1514	2.3389	2.4227	2.4973
	9	2.2871	1.0739	0.892	1.7967	1.1663	1.0704	1.7509	1.5838	1.2669	1.9592	2.0541	2.1831	2.2442
	10	2.1494	1.1878	0.77165	1.3729	1.4469	1.2326	1.8754	1.0461	1.4937	1.6187	1.7873	1.9145	2.1823
	11	2.5044	1.439	1.0272	1.5033	1.2208	1.0415	2.1541	1.6652	1.4816	2.0277	1.8739	2.3092	2.4
	12	2.601	1.7269	1.1663	2.3721	2.0078	1.8411	2.3363	1.8105	2.0122	2.1467	2.3402	2.4198	2.494
Block 2	13	2.3373	1.1184	1.1807	1.6292	1.4732	1.266	2.0136	1.7434	1.477	2.0028	2.1525	2.1875	2.2314
	14	1.9942	1.1611	0.75925	1.7918	1.4477	1.5261	1.5953	1.1969	1.2189	1.6114	1.7114	1.7923	1.9549
	15	2.4496	1.7515	1.2189	1.981	1.556	1.415	1.8805	1.5623	1.5693	2.0378	2.1785	2.2694	2.3386
	16	2.5455	1.7532	1.4012	2.1846	1.8553	1.6746	2.0643	1.6814	1.8526	2.358	2.235	2.3009	2.3671
	17	2.2888	1.203	0.94131	1.7257	1.3359	1.2575	1.2856	1.1389	1.0284	1.7346	1.9238	2.0656	2.2039
	18	2.6723	1.6409	1.6001	2.1278	1.9031	1.662	1.9979	1.8625	1.6608	2.1976	2.3139	2.3878	2.5554
	19	2.5518	1.7492	1.4036	2.1868	1.8584	1.6715	2.0681	1.6765	1.8558	2.358	2.2314	2.3029	2.3656
	20	2.4412	1.7492	1.2403	1.9759	1.5383	1.4263	1.8739	1.57	1.5783	2.033	2.1721	2.2701	2.3367
	21	1.9851	1.1579	0.78694	1.7851	1.4516	1.5354	1.5947	1.2109	1.2287	1.6253	1.7017	1.7929	1.9596
	22	2.6309	1.6715	1.521	2.1448	1.759	1.7126	1.7228	1.6448	1.5824	2.1603	2.2861	2.4162	2.5624
	23	2.6755	1.4732	1.4311	2.2956	1.7811	1.8682	2.3768	1.7906	2.1533	2.2638	2.3552	2.4844	2.6086
	24	2.6771	1.4793	1.4343	2.2962	1.8165	1.8956	2.3624	1.8272	2.1939	2.3056	2.3545	2.4918	2.6044

Table 9

Log Error Data: Experiment I

	Ss	Treatments in Latin Square Orders											
Block 1	1	1.7504	1.9242	2.3552	2.2375	1.7102	1.3888	1.7054	1.5967	1.863	2.4604	1.909	0.97833
	2	1.0152	2.1545	2.0242	1.4793	2.3982	1.6589	1.4359	1.5026	1.2198	1.0531	2.3062	1.8779
	3	2.1167	2.3918	1.8421	1.8911	1.687	2.5107	1.4142	1.1303	1.9291	1.6114	1.8966	1.7305
	4	2.3681	1.1745	1.6312	1.8331	1.9544	2.3263	1.8692	1.7923	1.912	1.7352	2.1868	1.2316
	5	1.744	2.3286	2.2663	1.6371	1.6396	2.2364	2.4841	2.6071	1.1632	2.346	2.1163	1.2139
	6	1.4989	1.6101	1.909	0.78694	1.208	1.2287	2.1183	1.789	1.9203	1.0908	1.4493	1.3601
	7	1.7364	1.7084	2.2875	1.3191	2.4242	2.151	1.5672	1.2509	1.9169	2.0273	1.0555	2.4777
	8	2.337	1.7257	2.4973	2.1514	1.1673	2.3746	2.0158	2.0145	1.84	2.3389	1.8132	2.4227
	9	1.9592	2.2442	1.0739	1.7509	1.2669	2.0541	0.892	2.1831	1.5838	1.7967	1.0704	1.1663
	10	1.1878	1.4937	0.77165	2.1823	1.8754	1.4469	1.6187	1.2326	1.7873	1.9145	1.3729	1.0461
	11	1.2208	1.0415	1.6652	2.3092	1.5033	1.4816	1.8739	2.0277	2.4	1.0272	1.439	2.15441
	12	2.4198	1.8105	1.8411	2.0078	2.3402	1.1663	2.3721	2.3363	1.7269	2.0122	2.494	2.1467
Block 2	13	1.6292	1.4732	2.1875	2.1525	1.7434	1.1184	1.266	1.477	2.0028	2.2314	2.0136	1.1807
	14	0.7593	1.5953	1.6114	1.2189	1.9549	1.1969	1.1611	1.7918	1.4477	1.5261	1.7923	1.7114
	15	2.1785	2.2694	1.556	1.981	1.415	2.3386	1.5623	1.2189	1.8805	1.7515	2.0378	1.5693
	16	2.3671	1.4012	1.8526	1.7532	2.358	2.3009	2.0643	1.6814	2.1846	1.8553	2.235	1.6746
	17	1.2575	1.9238	1.7257	1.1389	1.3359	1.7346	2.0656	2.2039	0.9413	1.2856	1.0284	1.203
	18	1.6608	2.1976	1.9979	1.6001	1.6409	1.662	2.5554	2.3139	2.3878	1.8625	1.9031	2.1278
	19	1.6765	2.1868	2.2314	1.6715	2.3029	2.0681	1.8584	1.7492	1.8558	2.358	1.4036	2.3656
	20	1.8739	1.7492	2.3367	2.033	1.2403	1.9759	1.5783	1.5383	1.4263	2.1721	1.57	2.2701
	21	1.6253	1.9596	1.1579	1.5947	1.2287	1.7017	0.7869	1.7929	1.2109	1.7851	1.5354	1.4516
	22	1.6715	1.5824	1.521	2.5624	1.7228	1.759	2.1603	1.7126	2.2861	2.4162	2.1448	1.6448
	23	1.7811	1.8682	1.7906	2.4844	2.2956	2.1533	2.3552	2.2638	2.6086	1.4311	1.4732	2.3768
	24	2.4918	1.8272	1.8956	1.8165	2.3545	1.4343	2.2962	2.3624	1.4793	2.1939	2.6044	2.3056

Table 10

Log Transformed Data: Experiment II

Ss	Treat-ments	Block 1 A(Steady)	Block 1 B(Flicker)	Ss	Treat-ments	Block 2 A(Steady)	Block 2 B(Flicker)
1	1	2.3341	2.1314	6	1	2.3878	1.9407
	2	2.4286	1.9199		2	2.3771	1.6525
	3	2.3523	2.0769		3	2.3504	1.9902
	4	2.3618	1.9838		4	2.4081	1.7727
	5	2.3696	1.9924		5	2.4024	1.7399
2	1	2.3832	2.3839	7	1	2.1381	1.6286
	2	2.326	2.2411		2	2.0807	1.159
	3	2.3786	2.4075		3	2.1094	1.7299
	4	2.3687	2.1525		4	2.1721	1.6088
	5	2.3237	2.3152		5	2.2006	1.5504
3	1	2.1641	2.1606	8	1	2.5185	2.1179
	2	2.3652	2.2878		2	2.5639	2.0533
	3	2.3637	2.3302		3	2.4616	2.066
	4	2.5185	2.2949		4	2.6511	2.1432
	5	2.3891	2.1211		5	2.5276	2.1838
4	1	2.2905	2.1138	9	1	2.3046	1.8088
	2	2.3549	1.9502		2	2.3687	1.7699
	3	2.3072	2.1365		3	2.3299	1.9378
	4	2.3402	1.961		4	2.4006	1.763
	5	2.3878	1.709		5	2.1789	1.4876
5	1	2.2888	2.1766	10	1	2.461	2.1086
	2	2.1875	1.9879		2	2.3615	1.9478
	3	2.2611	2.0711		3	2.5361	2.192
	4	2.2488	1.945		4	2.3814	1.9559
	5	2.3758	1.954		5	2.3674	1.6664

Table 11

Log Error Data: Experiment II

	Ss	Treatments in Latin Square Orders				
Block 1	1	0.20268	0.37719	0.50877	0.37804	0.27539
	2	0.00852	0.08491	0.21615	-0.02893	-0.00061
	3	0.22361	0.3348	0.00345	0.26801	0.07744
	4	0.17071	0.17667	0.67886	0.40467	0.37917
	5	0.19967	0.30388	0.19	0.11218	0.42186
Block 2	6	0.44719	0.66255	0.72458	0.63546	0.36027
	7	0.65016	0.92172	0.56333	0.37952	0.50952
	8	0.50793	0.39556	0.40064	0.34379	0.51065
	9	0.39209	0.49575	0.69126	0.59883	0.6376
	10	0.41367	0.42554	0.34405	0.35242	0.70099